Domain Walls that Conduct Electricity

Exploring the Ultimate Nanoscale for Future Electronics

Researchers in the group of MSD investigator Ramamoorthy Ramesh, in collaboration with other MSD and University of California scientists, have shown that nano-scale “domain walls” in otherwise insulating bismuth ferrite ($BiFeO_3$ – BFO) can conduct electricity. As domain walls can be readily written, erased, or moved, this newly discovered phenomenon may represent an important new nanoscale feature for future electronics.

The defining characteristic of a “ferroic” material is that it has a property whose orientation can be controlled using an applied field. The most familiar ferroic property is ferromagnetism: it has been known since ancient times that the “north and “south” directions in iron can be switched with an applied magnetic field. However, the term ferroics has been broadened and now includes compounds and properties having nothing to do with iron. For example, in ferroelectrics, the electrical polarization can be switched between orientations by an applied electric field. In ferroelastic materials – “shape-memory” alloys, for example – applied stress can cause a reversible spontaneous change in orientation or crystal structure.

Within a ferroic material, there may be domains of differently oriented regions; the boundary between them (e.g. between N and S oriented domains in a ferromagnet) is called a domain wall. Recently, it has been theorized that domain walls, which are typically only a few atoms thick, can have vastly different properties from the domains they separate.

In this work, “piezoresponse force microscopy” (PFM) was used to study the micron sized domain walls between regions of different electrical polarization in carefully prepared single crystal films of bismuth ferrite. When the scan probe was lowered to the surface to image the local conductivity, the domains were shown to be nonconducting, as expected since BFO is an insulator. Surprisingly however, certain domain walls exhibited electrical conductivity. Moreover, their conductivity depended on the angular difference in the direction of the polarization on opposite sides of the domain wall.

To determine the origin of this unexpected conductivity, the researchers used high-resolution transmission electron microscopy (TEM) at Berkeley Lab’s National Center for Electron Microscopy to image the atomic arrangements at the domain walls. BFO has three types of domain walls, which separate domains with either 71°, 109° or 180° differences in the direction of polarization. By comparing the atomic structure of a nonconducting 71° domain wall to that of a conducting 109° domain wall, the researchers found a clear difference in local structure. Subsequent theoretical calculations performed at UC Santa Barbara revealed the microscopic mechanism responsible for the effect – a tiny displacement of the iron atoms.

Finally, the researchers demonstrated a simple device. By using the PFM probe to locally switch the domains in a narrow strip of BFO, they showed that the conductance across the strip could be increased or decreased incrementally by reorienting the domains, thus increasing or decreasing the number of conducting domain walls linking the contacts.

Domains walls may represent an important new nanoscale feature; they enable one to embed (and also move) an atomic scale conducting sheet inside of an insulator. In this sense, the domain walls are discrete functional entities, which may be addressed and sensed, suggesting potential utility in novel nanoelectronic applications.

R. Ramesh (510)643-8202 , Materials Sciences Division (510 486-4755), Berkeley Lab.

J. Seidel, L.W. Martin, Q. He, Q. Zhan, Y.-H. Chu, A. Rother, M. E. Hawkridge, P. Maksymovych, P. Yu, M. Gajek, N. Balke, S. V. Kalinin, S. Gemming, F.Wang, G. Catalan, J. F. Scott, N. A. Spaldin, J. Orenstein and R. Ramesh, Conduction at domain walls in oxide multiferroics, Nature Materials (2009).

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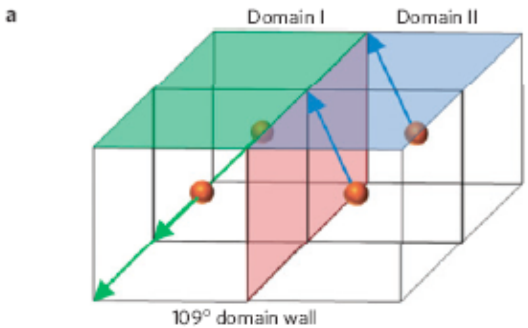
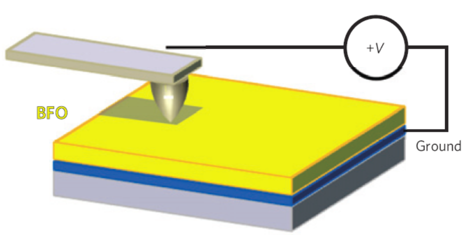
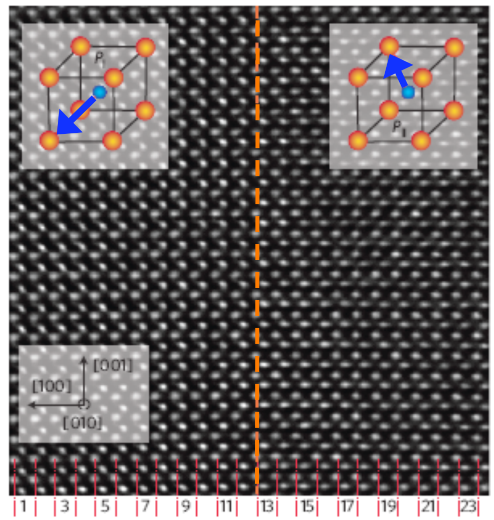


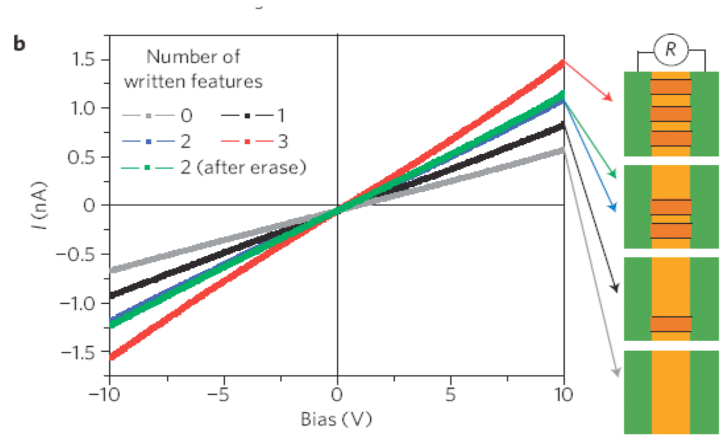
Bismuth ferrite is a ferroelectric material with regions or "domains" with a built-in electrical polarization of differing direction. The schematic above illustrates a boundary (red) between two domains whose electrical polarization, indicated by the green and blue arrows, differ by 109° .



Measurements of the local electrical polarization and conductivity in a thin film of $BiFeO_3$ (BFO) were performed using scanning probe microscopy.



Due to the crystal structure of bismuth ferrite, domain walls can separate regions whose polarization is offset either 71º, 109º or 180º from each other: only the 109° and 180° walls are electrically conducting. A high resolution electron microscopy image of a 109° domain wall is shown. A small shift of the Fe atom (blue) with respect to the Bi atoms (orange) is discerned at the boundary; this allows the domain walls (dotted orange line), which are just two nanometers wide, to conduct electricity at room temperature.



Scanning probe tip can be used to control the current in a structure by altering the number and arrangement of conducting domain walls in bismuth ferrite (orange) between electrodes (green). In the example above, the resistance R decreases to allow greater current flow between the electrodes as the number of conducting domain walls is increased from zero (gray line) to three (red line). The overlapping blue and green lines, from writing, erasing, and then rewriting two lines demonstrate that the process could be used for reversible information storage.